research review

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Interactions of Ultrasound and Electrons in Metals

MAX SWERDLOW, Directorate of Physical Sciences, AFOSR

During the past 10 years, a powerful new technique has evolved for studying the electronic structure of metals. Ultrasonic waves, at frequencies from a few Mc/s (megacycles per second) to a few hundred Mc/s and, more recently, up to 10 Gc/s (gigacycles per second), are propagated through metal samples held at very low temperatures. In metals at very low temperatures, the attenuation of ultrasonic-frequency sound waves is very large. The interesting feature is that the attenuation is caused by interaction of the sound wave and the conduction electrons. Because of this, the attenuation has a strong dependence on the magnitude of an applied external magnetic field. Variations of the attenuation as a function of applied magnetic field and/or of temperature, can be interpreted to give information about the Fermi surface* of a metal and/or about the superconducting properties of the metal.

At liquid-helium temperatures, the conduction electrons in a metal interact strongly with ultrasonic waves and, in the presence of a magnetic field, this interaction can give rise to several types of oscillatory behavior in the ultrasonic attenuation. Measurements of these oscillations, called geometric resonances, quantum oscillations, and ultrasonic cyclotron resonances, permit calculations of linear dimensions, cross-sectional areas, and curvatures of the Fermi surface of the metal under investigation, respectively; knowledge of these parameters is necessary for a complete understanding of the physical properties of a metal.

When a metal becomes superconducting, the interaction between the electrons and ultrasonic waves changes drastically, greatly

The Fermi Surface is an abstract concept which represents a constant—energy surface in momentum space. The closed contour or envelope separates the filled from the unfilled energy levels in the various electronic states of solids. The Fermi surface is, in a sense, the three-dimensional analog of the Fermi level, which is the point on an energy-level diagram corresponding to the top of the Fermi distribution of electrons. The Fermi surface is not a surface in real space, but a mathematical model of how electrons behave in a solid. The concept is used to describe the electronic transport properties, such as the conduction of electricity, heat and sound in solids. For more complete discussions of the significance of the Fermi surface, the reader is referred to The Fermi Surface, edited by W. A. Harrison and M. B. Webb, and published by John Wiley and Sons, Inc., New York, 1960. This publication reports on the proceedings of an international conference held at Cooperstown, New York, August 1960, and sponsored by the Air Force Office of Scientific Research and the General Electric Research Laboratory.

reducing the ultrasonic attenuation. If the temperature of the metal is raised, or if a magnetic field is applied to quench the superconductivity, the electrons come into full force again, causing a marked increase in attenuation. As Bardeen, Cooper, and Schrieffer (B.C.S.) predicted (1), and Morse and Bohm (2) first demonstrated, the ratio of the superconducting attenuation to the normal attenuation can be related to the B.C.S. energy gap, a fundamental parameter in the theory of superconductors.

In the following sections, the physics of electrons in metals will be outlined, and the origins of some of the phenomena dependent on magnetic fields, as well as the sharp decrease in attenuation in the superconducting state, will be discussed. A number of examples of experimental work, many carried out under AFOSR sponsorship by the ultrasonic group at Wayne State University, are presented herein. The list of references, and the author citations given in this article, are necessarily incomplete and abbreviated. For more details, the reader is referred to "Investigations of the Electronic Structure of Metals Using Ultrasonic Techniques," (3) a review article by N. Tepley which contains a rather complete set of 128 references.

ELECTRONS IN NORMAL METALS

The simplest model of a metal consists of a lattice of fixed positive ions immersed in a sea of conduction electrons free to move through the lattice. The energy, E, of a free electron is related to its momentum by the relation $E = p^2/2m$, where p is the momen-

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JACOB SEIDEN
Editor

from the Editor

Many of our readers are aware of the fact that the National Research Council of Canada assumed management operation of the testing facility at the Churchill Research Range (CRR) on 1 January 1966. Since CRR is no longer a member of the OAR family, it should have been removed from the listing of OAR organizations shown on the lower portion of the format preprint (page 1). However, as a measure of economy, this deletion will not be effected for another month or two, after the current stock of format preprints is used up.

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tum and m is the mass of the electron. Quantum mechanics requires that an electron in a metal can exist only in any one of a set of discrete energy states. Further, if the temperature of the sample is well below the "Fermi temperature" (about 60,000 degrees K for a typical metal), each of the lowest-lying allowed energy states will be occupied by an electron, up to that state, called the Fermi level, which exhausts the entire supply of electrons available in the sample. The surface of constant energy in momentum space at the Fermi level is called the Fermi surface. By virtue of the particularly simple energy-momentum relation for the free electron model, the Fermi surface for this model is a sphere of radius (in momentum units) $p = \sqrt{2mE_f}$, where E_f is the energy of the Fermi level.

If one takes into account the interaction of the electrons with the lattice, the energy-momentum relation, and hence the Fermi surface, is no longer as simple. In fact there may be discontinuities in the energy as a function of momentum; these discontinuities occur on a surface (still in momentum space) called the Brillouin zone** boundary. The positions of these boundaries are strictly a consequence of the crystal structure. It turns out to be meaningful to introduce a repeated zone scheme as shown in Figure 1. A series of Brillouin zones are packed together so that the Fermi surface, wherever it touches the zone boundary, is connected to a repetition of itself. This construction is useful for visualizing the orbits of electrons not only in momentum space but also in real space. In the presence of a magnetic field, the orbits in momentum space are intersections of the Fermi surface with planes perpendicular to the field; in real space, the orbits are helices, the projections of which, in a plane perpendicular to the field, are similar in shape to the orbits in momentum space, but rotated by 90 degrees, and scaled by a factor inversely proportional to the magnetic field. Hence a Fermi surface, multiply-connected across Brillouin zone boundaries, can give rise to a whole series of complicated electron orbits as indicated in Figure 1.

The importance of the Fermi surface lies in the fact that only electrons lying near the Fermi surface have nearby unoccupied energy states into which they can make transitions. Electrons deep inside the Fermi surface are surrounded by occupied states, and hence cannot take part in transport processes. Thus, to the materials scientist working with a particular metal, a knowledge of its Fermi surface is vital.

When an ultrasonic wave propagates through a metal, an electron on the Fermi surface experiences forces causing it to depart from the Fermi surface. Hence, there must be an electromagnetic field consistently associated with the ultrasonic wave to maintain charge neutrality in the sample. Energy is transferred from the ultrasonic wave to the electron system through this electromagnetic field, and this energy is, in turn, lost by the electron through collisions with phonons (lattice vibrations) or impurities. If the electrons affected by the interaction traverse a mean free path that is long compared to the ultrasonic wave length, they can absorb large amounts of energy between scatterings, and the attenuation can be quite large. In general, this is the situation which must prevail if information about the Fermi surface is to be obtained. Hence, very low temperatures are required (to reduce thermal lattice vibrations), and very pure metal samples are required (to reduce impurity scattering).

If a magnetic field is applied in a direction perpendicular to the propagation direction of the ultrasonic wave, electrons on the Fermi surface will move through regions of local lattice strain. If the mean free path is sufficiently long, the electrons will complete several trips around their orbits (see Fig. 1) before scattering, being subjected during each trip to the local electric field

***The Brillouin Zone is an abstract concept pictured in the same momentum space as the Fermi surface. It is represented by a polyhedron which can often be constructed in "k-space" from considerations of the wave vectors of the various electronic states characteristic of the energy band theory of solids, the crystal lattice and its symmetry. In the study of complex metals and alloys, where there may be several overlapping energy bands, the geometry of the zones plays an important role.*

forces due to the ultrasonic wave. In general, the electrons will be affected most by the forces at the orbit extrema along the direction in which the wave propagates; at these positions, the electron will be travelling parallel to the wave front. The conditions under which geometric resonance arises are shown in Figure 2. The magnetic field is adjusted to make the dimension, d, of the orbit along the propagation direction an odd number of half wave lengths, so that the electron samples opposite phases of the wave at opposite extrema of its orbit, leading to a minimum in the ultrasonic attenuation. If now the field is decreased until the dimension d in figure 2 is an even number of half wave lengths, the effects at the two extrema will cancel; but, if the field is decreased still further, again there will be a minimum in absorption when d is an odd number of half wave lengths. Hence, as the field, H, is swept, the attenuation will oscillate as a function of 1/H with a period

$$\Delta\left(\frac{1}{H}\right) = \frac{e\lambda}{cP_y}$$

where P_y is an extremal dimension of the Fermi surface in the p_y direction, e is the electron charge, c the speed of light, and λ the ultrasonic wave length. Measurements of these geometric resonance oscillations provide a caliper of the Fermi surface in the direction perpendicular to both the field

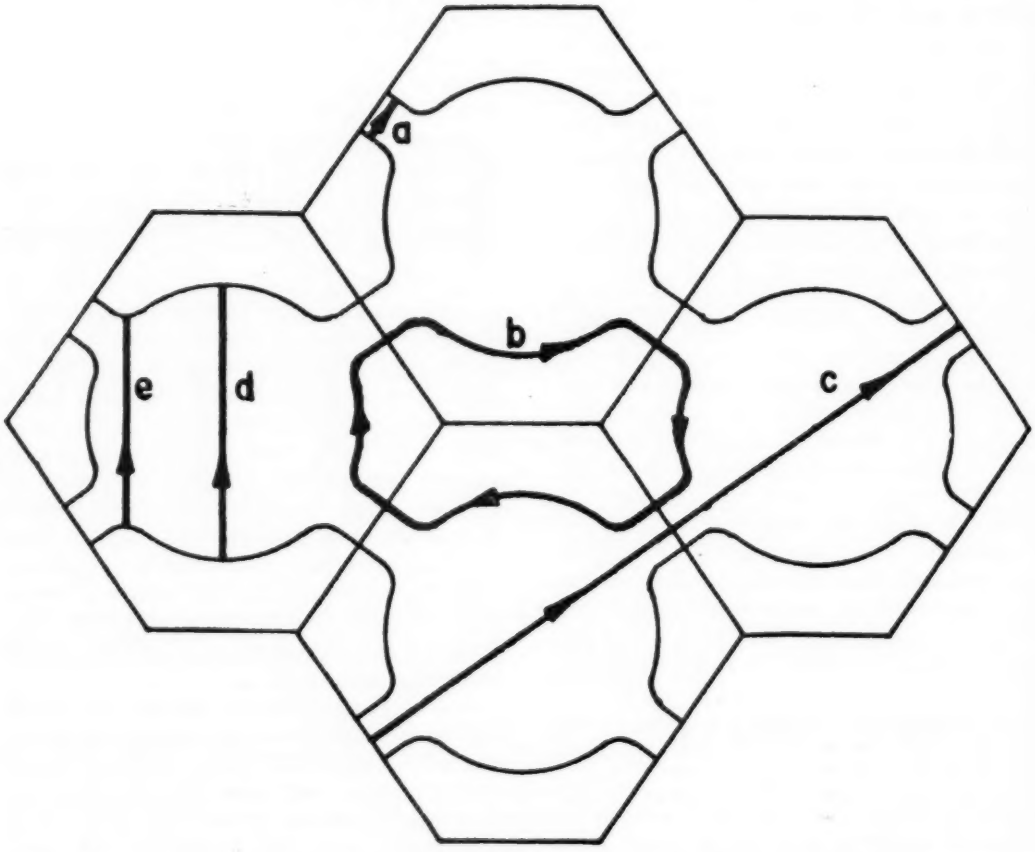

Figure 1 Extended zone scheme showing some possible orbits on a noble metal Fermi surface: (a) neck orbit; (b) dog's bone; (c) open orbit; (d) central belly orbit; and (e) off-center belly orbit. [From V. J. Easterling and H. V. Bohm, Phys. Rev., 125, 812, 1962]

direction and the sound propagation direction. The theory of geometric resonances was developed primarily by Pippard (4) and Cohen, Harrison, and Harrison (5). Many references to geometric resonance experiments will be found in the review article already cited (3).

Figure 3 is a photograph of an actual recorder chart of geometric resonance oscillations observed in silver by Easterling and Bohm (6). They verified that the Fermi surface of this metal is essentially a sphere pulled out in the [111] directions to make contact with the hexagonal faces of the Brillouin zone. In the repeated zone scheme, these distorted spheres are joined together by necks to form a multiply-connected Fermi surface. The three noble metals, Ag, Au, and Cu, have Fermi surfaces which are similar in shape; detailed ultrasonic measurements were made by Bohm and Easterling (7), among others. In contrast to the relatively simple Fermi surfaces of the noble metals (which have only one valence electron per atom), aluminum (with three valence electrons per atom) has a more complicated Fermi surface with both concave and convex portions making orbit identification difficult (8). There are many metals the Fermi surfaces of which are so complicated that their detailed shapes are not yet known. Most recently, the Wayne State group has been engaged in an investigation of the almost completely unexplored Fermi surface of mercury.

Another type of oscillation in the ultrasonic attenuation is ultrasonic cyclotron resonance. Unlike geometric resonances which arise from a spatial coincidence between the electron orbit and the sound wave, the cyclotron resonance arises when the electron's orbital period is an integral multiple of the ultrasonic wave period; this effect provides a measurement of the effective masses of electrons on the Fermi surface. For the effect to be observed, electrons must experience the same force at corresponding points along their orbits during each of many traversals of an orbit. Hence, a necessary condition for the effect is that the electron's relaxation time be very long compared to the ultrasonic period, a condition which is approximately 500 times more severe than the condition on the mean free path necessary for geometric resonance. For this reason, the effect has as yet only been reported in gallium (9,10). However, as higher purity metal samples become available, and higher ultrasonic frequencies are utilized, the ultrasonic cyclotron resonance should become a powerful tool for investigating the Fermi surface. In part, to achieve this purpose, Tepley has extended the fre-

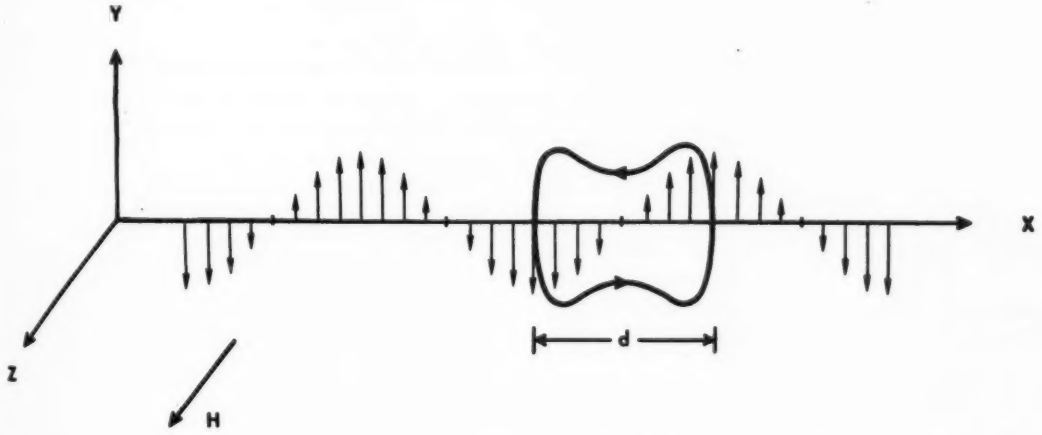

Figure 2 The conditions for geometric resonance: when the dimension, d, of the electron orbit is an odd number of half wave lengths, there will be a minimum in attenuation. (From N. Tepley, Proc. I.E.E.E., to be published)

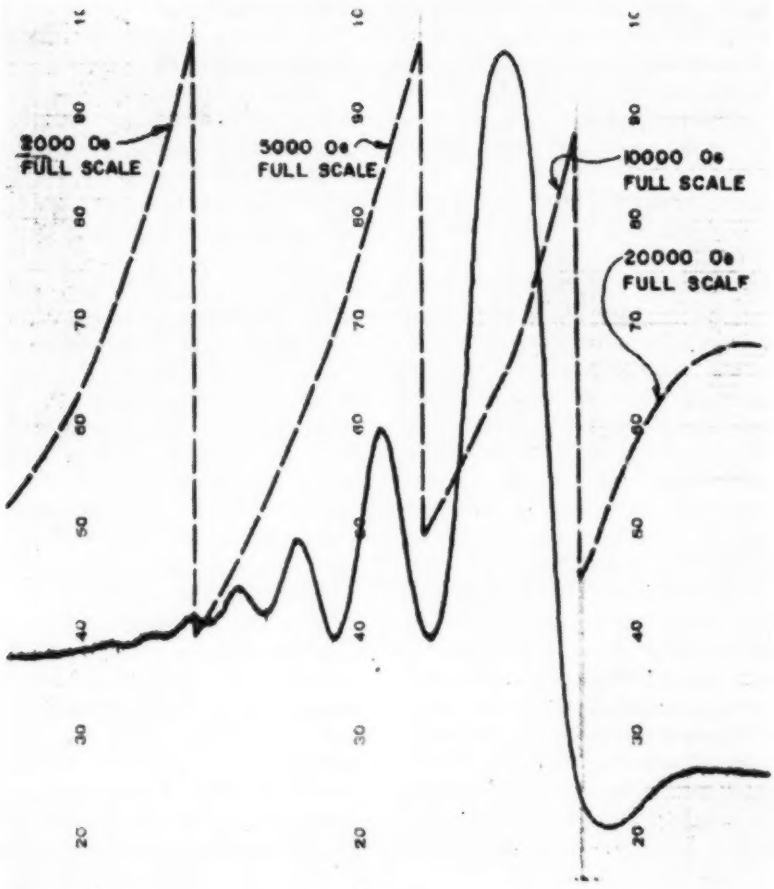

Figure 3
Actual recorder chart of ultrasonic pulse height (solid curve) as a function of magnetic field (dashed lines) in silver. [*From V. J. Easterling and H. V. Bohm, Phys. Rev., 125, 812, 1962*]

quency range of his ultrasonic experiments in metals to 10 Gc/s. The theory of ultrasonic cyclotron resonance is given by Cohen, Harrison, and Harrison (5) and Kaner (11).

A third type of oscillation in the ultrasonic attenuation as a function of magnetic field is called the quantum oscillation because it arises as a result of the Bohr quantum rule, $\oint pdq = nh$. (In this expression, q is a cyclic coordinate of an electron, p its canonically conjugate momentum, h is Planck's constant, n is any integer, and the cyclic integral implies that the integration is carried out over one complete period of the motion.) Hence, the total area bounded by an electron orbit (in momentum space) is quantized,

$$A = (n + \frac{1}{2})\, 2\pi eh\, H/c;$$

in this expression h is Planck's constant

divided by 2π. As the magnetic field is swept, successive quantized orbits (called Landau levels) pass through the Fermi surface, giving rise to small oscillations in the energy of the electron gas. This effect gives rise to the de Haas-van Alphen oscillations in magnetic susceptibility, to Shubnikov-de Haas oscillations in the electrical resistivity, and to quantum oscillations in the ultrasonic attenuation. The theory of the quantum oscillations was first given by Gurevich, Skobov, and Firsov (12), and by Quinn and Rodriquez (13). These effects give a measure of cross-sectional areas of the Fermi surface, generally at extremal cross sections. Quinn (14) has shown that, under properly arranged circumstances, the quantum oscillations may even measure selected nonextremal cross sections.

Bohm and Mackinnon have reported on quantum oscillations in zinc (15). More recently Wallace, Tepley, Bohm, and Shapira (16) have used a 110-kilogauss solenoid at the National Magnet Laboratory to study intriguing quantum oscillations in chromium. When cooled through its Neel temperature (312° C) in zero magnetic field, chromium is a body-centered cubic metal. However, when chromium is cooled in a moderately high field, antiferromagnetic ordering takes place, destroying the cubic symmetry. Since the Fermi surface must reflect the symmetry of the crystal, these investigators studied quantum oscillations in chromium cooled in zero field (16), and are now conducting experiments on chromium cooled in a field of about 80 kilogauss. Indeed, different quantum oscillation periods were observed in the two cases. In addition, in the former case, they found a difference between virgin runs (the very first time the field was applied to the sample), and subsequent runs. Additional quantum oscillation periods were found in the nonvirgin runs. These workers are also investigating the possibility that very high fields may alter or destroy the antiferromagnetic order. As this research proceeds, it is hoped a better understanding of antiferromagnetic phenomena will result.

ELECTRONS IN SUPERCONDUCTORS

The ultrasonic attenuation in a superconductor decreases very rapidly as one lowers the temperature of the sample through the critical temperature, T_c. According to the B.C.S. theory of superconductivity (1), this occurs because, below T_c, there exists a state lower in energy than the usual ground state of a normal metal in which a fraction of the electrons exist in bound pairs. To excite an electron from a pair into the normal Fermi sea requires a finite energy $\Delta(T)$. The ultrasonic attenuation is proportional to N, the number of (unpaired) electrons per unit volume (17); thus, Bardeen, Cooper, and Schrieffer (1) show that the ratio of normal to superconducting attenuation is just

$$\frac{\alpha_s}{\alpha_n} = 2/\left\{\exp[\Delta(T)/kT]+1\right\}$$

where k is Boltzmann's constant and T is the temperature. Ultrasonic attenuation provides a powerful way to study the B.C.S. energy gap ($2\Delta(T)$), since α_s and α_n can be measured at the same temperature by turning on a magnetic field to quench the superconductivity. In particular, since the only electrons which take part in the attenuation process are those which have a component of velocity along the sound propagation direction equal to the velocity of sound, and since, for a typical metal, the Fermi velocity of the electrons is 500 times the velocity of sound, the "effective" electrons are those travelling almost perpendicular to the sound propagation direction, that is to say, those in a narrow "equatorial band" on the Fermi surface; hence, the ultrasonic technique can be used to investigate the directional anisotropy of the energy gap of a superconductor.

At the present time, the Wayne State group is investigating the energy gap in gallium using 9 Gc/s ultrasound. At this high frequency, the ultrasonic phonon energy is an appreciable fraction of the B.C.S. energy gap, so that it may be possible to observe ultrasonically for the first time direct excitation of electrons across the energy gap. These workers have also undertaken an investigation of the energy gap in mercury.

EXPERIMENTAL TECHNIQUES

Most of the experimental techniques used in ultrasonic attenuation experiments are discussed by Tepley (3). The vast majority of all experiments use the pulse echo technique in which short bursts of rf (radio frequency) power are applied periodically to a quartz transducer bonded to the surface of a metal sample. The transducer converts this to sound frequency power which propagates through the crystal and is either reconverted to an rf pulse by a second matched transducer on the opposite face of the sample, or "echoes" back to the first transducer where it is reconverted to rf. In either case, the pulse is received, amplified, rectified, and displayed on an oscilloscope, and/or its amplitude is plotted on a recorder as a function of magnetic field or temperature. A particularly satisfactory system has been described by Kamm and Bohm (18). Recently, Wallace, Tepley, Bohm, and Shapira (16) devised a technique for performing measurements at two different frequencies simultaneously. In their arrangement, one ultrasonic system was triggered by a signal from a second ultrasonic system adjusted in such a way that its rf pulses were delayed some 50 microseconds from those of the first system. Pulses from both transmitters were applied to the same transducer and the resulting echoes, well separated in time, were viewed on separate oscilloscopes, separately gated, and recorded on separate recorders. Figure 4 shows a block diagram of a typical ultrasonic attenuation experiment. Figure 5 shows a sample holder for ultrasonic experiments at frequencies from 10 Mc/s to one Gc/s. The sample can be rotated by more than 180° from outside the helium Dewar by means of a worm-gear arrangement. The entire sample holder fits easily into a 36-mm I.D. helium Dewar as does the 9 Gc/s sample holder shown in Figure 6.

Through the use of ultrasonic waves of frequencies from 10 Mc/s to 10 Gc/s (a

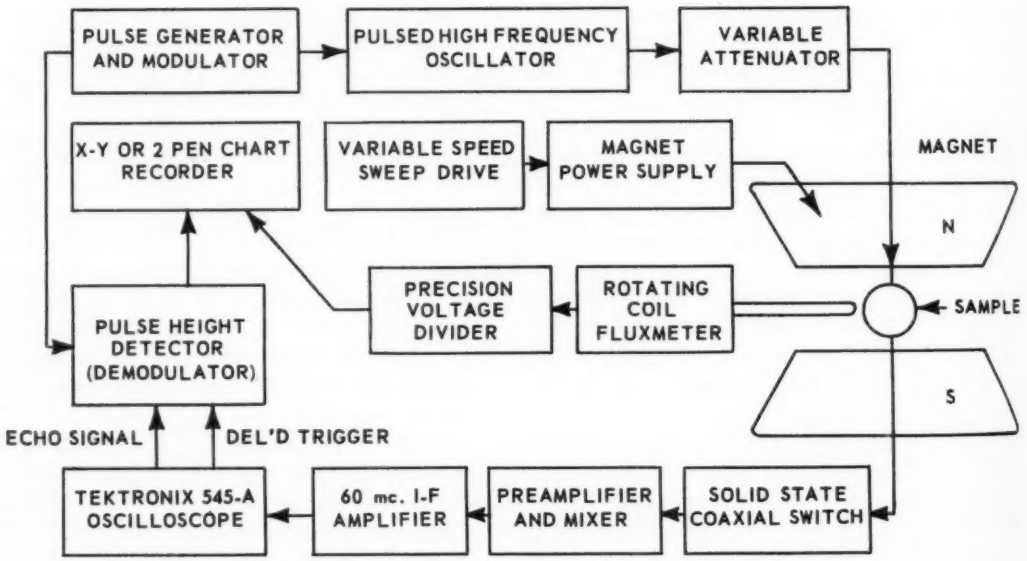

Figure 4 Block diagram of typical magnetoacoustic experiment. [*From G. N. Kamm and H. V. Bohm, Rev. Sci. Instr., 33, 957, 1962*]

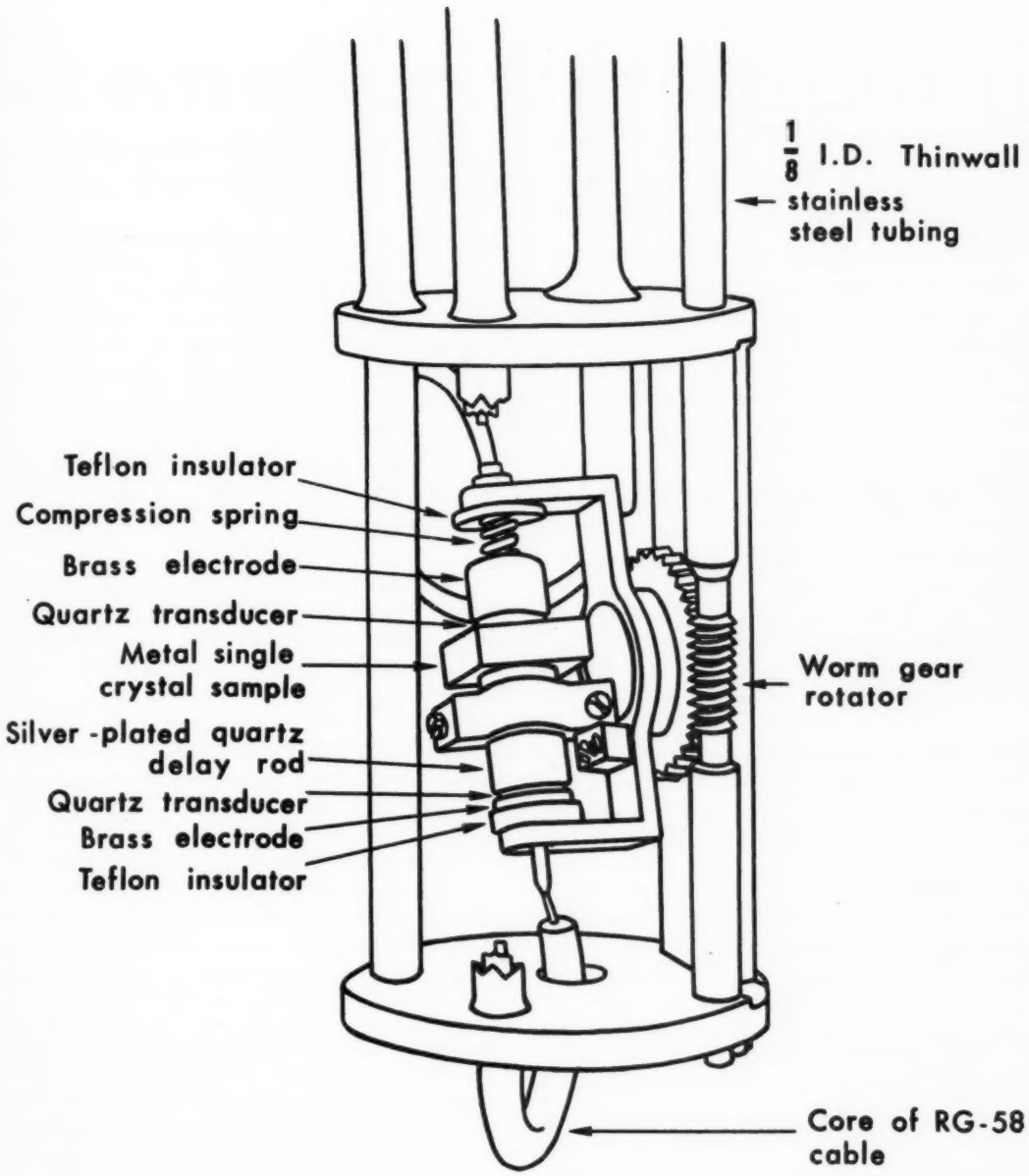

Figure 5 Rotating sample holder for ultrasonic attenuation experiments from 10 Mc/s to one Gc/s. (From N. Tepley, Proc. I.E.E.E., to be published)

range believed wider than that available at present in any other laboratory) on increasingly pure metal samples, the Wayne State University group is continuing a wide variety of experiments aimed at increasing our knowledge and understanding of the properties of metals and the electronic and magnetic phenomena associated with metals.

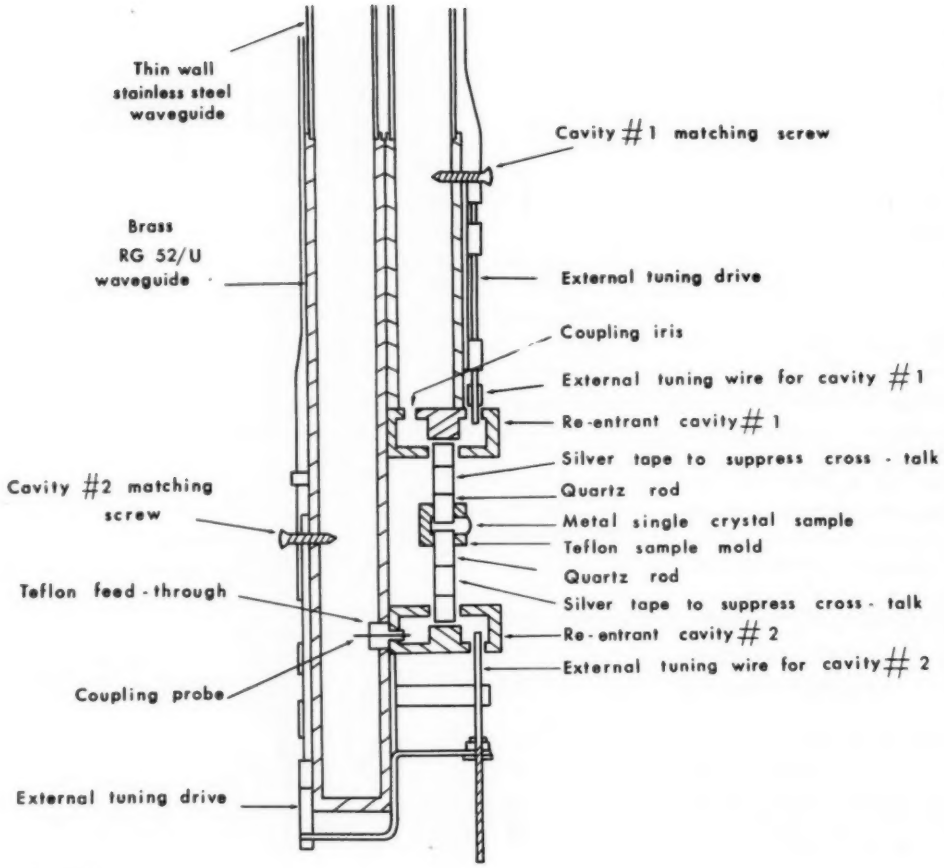

Figure 6

Sample holder for ultrasonic attenuation experiments at 9 Gc/s. (From N. Tepley, Proc. I.E.E.E., to be published)

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locomotion automata

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The development of mechanical means for land locomotion has been restricted almost entirely to wheeled or tracked vehicles. While such vehicles are admirably suited to travel on relatively smooth surfaces, observation of the motion of animals over very rough or soft ground reveals that legs are better suited than wheels to locomotion over difficult terrain. This suggests that natural locomotion systems ought to be studied more seriously as potential prototypes for off-the-road vehicles.

The design and analysis of natural and synthetic locomotion machines making use of legs rather than wheels can be approached in several ways. It is possible, for instance, to regard the dynamical behavior of such a system from the point of view of classical mechanics. Unfortunately, the differential equations of motion for machines or animals with articulated limbs are so complicated that a sufficiently accurate model of this type is very difficult to obtain and verify. Moreover, even if such a model were available, the complexity of the equations would very likely obscure some of the more fundamental aspects of locomotion and certainly would present a difficult control problem.

Dr. Robert B. McGhee of the University of Southern California, working under the sponsorship of the Joint Services Electronics Program, has recently found a way to circumvent many of the difficulties inherent in a classical treatment of locomotion. By dividing the motion of the limbs of legged locomotion machines into a distinct sequence of phases, Dr. McGhee has been able to construct a finite-state model for locomotion, thereby permitting the study of such machines as finite automata. The resulting theory is sufficiently general to permit either natural or artificial locomotion automata to be treated equally well and sufficiently complete to permit the synthesis of finite-state controllers for locomotion machines.

An artificial quadruped based on finite-state principles is now under construction at USC. This machine is furnished with a simple programmable controller capable of producing both the natural gaits of a horse and arbitrary artificial gaits. While the mechanical design of this automaton has not yet been completed, a leg with a powered knee and hip joint has been successfully cycled by a simple control circuit using only on-off inputs and outputs. Upon completion, the quadruped will provide a basis for further theoretical and experimental work relating to questions of stability, efficiency, etc., for legged locomotion machines in particular, and for finite-state control systems in general.

Dr. McGhee's research is part of the Joint Services Electronics Program at the University of Southern California, Los Angeles. This program, which is funded by AFOSR, is under the over-all direction of Prof. Z. Kaprielian, Chairman of the Department of Electrical Engineering. It is hoped that this synthesis of quadruped locomotion will provide a more suitable transportation machine for rough or soft terrain such as might be encountered in remote places on the earth, or on other planets. In the distant future, it is planned to incorporate balancing sensors, add an additional joint, and attempt locomotion of an artificial biped. Portions of the results of these studies are now being evaluated for practical application to prosthesis designs. ★

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SURVEY OF SPECTRAL ANALYSIS FOR GEOPHYSICAL DATA

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A survey of Fourier methods which are of importance in the analysis of geophysical data was recently presented at the Second Symposium on Geophysical Theory held in Rehovoth, Israel.

This survey, completed by E. J. Hannan of the Australian National University while serving as visiting professor at Johns Hopkins University, was supported by the Air Force Office of Scientific Research.

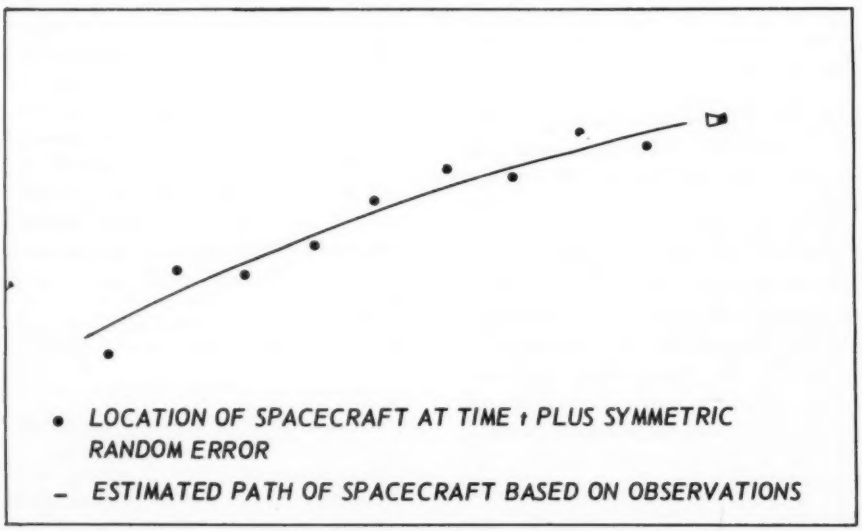
Fourier methods are widely used when symmetric conditions are imposed on a phenomenon being studied. For example, a symmetric condition might be random errors included in observations, while a phenomenon being studied might be the flight path of a spacecraft.

Three special cases of spectral methods which are of interest to geophysicists are discussed. They are: stationary random time functions; homogeneous spatial random functions; and homogeneous random functions on a sphere. Other subjects summarized are filtering and sampling, spectral estimation, and signal measurement in noise.

This survey is of value to geophysicists and mathematicians for several reasons. First, it is an authoritative and extremely up-to-date survey. Second, it contains bibliographical notes and references indicating where further information can be obtained. Finally, the survey is simply written and does not contain a single mathematical proof to discourage the nonmathematician interested in the subject of spectral analysis.

A copy of this survey, Technical Report No. 25, Spectral Analysis for Geophysical Data, by E. J. Hannan, may be obtained from the Mathematics Division, Air Force Office of Scientific Research. Also available is Technical Report No. 23, Aliasing, by E. J. Hannan. This research paper discusses in depth the problem which arises when a process is only partially observed. ★

EXAMPLE WHERE FOURIER METHODS ARE APPLICABLE



Hill's Equation

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General Physics Research Laboratory, ARL

Hill's equation is a kind of ordinary linear differential equation of second order. Its distinguishing feature (assuming its reduction to normal form) is a coefficient which is a periodic function of the independent variable. Mathieu's equation is a special case wherein the coefficient is simply a sine function. It arises in many diverse physical problems. Its original application, by G. W. Hill, was to his determination of the motion of the lunar perigee. Another application is to the motion of a pendulum with a vibrating support. It is well known that Mathieu's equation occurs in an analysis of the oscillations of an elliptical membrane and of the wave motion in an elliptical lake. In the realm of modern physics, Hill's equation--here a form of Schrödinger's equation--describes the motion of electrons in a hypothetical one-dimensional crystal which extends without limit in both directions. It is in this context that the equation is considered below.

The one-dimensional crystal has frequently been studied for the insight it provides, through a relatively simple picture, of behavior to be expected in the more realistic three-dimensional model. The motion of an electron is governed by the difference between its total energy and its potential energy--the product of the electronic charge and the crystal potential--due to its interaction with the other electrons and the nuclei. The coefficient that appears in the resulting equation is proportional to this difference, which possesses the periodicity of the crystalline lattice.

A wave mechanical requirement is that the solution of this equation be bounded. This is possible over certain ranges of values of the total electronic energy, called energy bands. Depicting the energy band structure of a crystal is basic to understanding its properties.

For a value of energy within a band the solution to this wave equation, according to Floquet's theorem, may be represented as a product of a periodic function and a wave function appropriate for a free electron. The momentum which this latter function would give to such a free particle is the effective momentum assigned the crystalline electron. The band structure, thus, is expressed as a relationship between the energy and the effective momentum. The energy of a free particle, both classically and wave mechanically, is proportional to the square of its momentum. For the electron in a crystal, of course, the relationship is more complex.

While solving a one-dimensional wave equation in general poses no particular difficulty, if one enlists the aid of the computer or numerical techniques, the desired insight into crystalline behavior would seem to favor an analytical approach. For instance, although a computer can readily supply a table listing the energies corresponding to chosen values of the effective momentum for a given crystal potential, a series of such tables corresponding to various crystal potentials would constitute a cumbersome way of studying the relation between the band structure and the crystal potential, the sensitivity of the former to minor changes in the latter. A more meaningful and simpler device would be to first relate the band structure directly to the crystal potential in a perhaps crude approximation through some Wentzel-Kramers-Brillouin (W. K. B.) type formula, and then successively to improve upon this until a desired accuracy is obtained.

A means for doing this has recently been developed at ARL. It resembles the W. K. B. method, which is inapplicable to Hill's equation in that, considered as an application of the related equation method, it employs the free electron wave equation (whose solutions are well known and easily expressed) as the related equation. A description of the method will appear in the Journal of Mathematical Physics.

Whether such a procedure can be extended to the three-dimensional model, which in general yields to band structure calculations only after considerable labor, is to be the subject of further study. ★

air condensation in rapidly expanding hypersonic flow

FRED L. DAUM, Fluid Dynamics Facilities Laboratory, ARL, and
DR. GEORGE GYARMATHY
Thermomechanics Research Laboratory, ARL

The hypersonic wind tunnel affords a method of testing models of aerodynamic bodies under simulated extremely high-speed flight conditions. To achieve the high Mach number flows, the test medium is expanded and accelerated through the wind-tunnel nozzle; however, in this process the stream pressure and temperature both decrease greatly. It is possible that this decrease is enough to reach and surpass the air saturation conditions. When this happens, the air must either start to condense or it becomes supersaturated. It is well known that under certain reservoir (stagnation) conditions, air condensation will occur in these nozzles and droplets of liquid air will form in the air stream. For this case the test data would be invalidated because the test medium no longer behaves as an ideal gas.

A common method of avoiding the problem of condensation in wind tunnels is by heating the air prior to the expansion so as not to reach saturation conditions. However, at very high Mach numbers, the stagnation temperatures required are so great that this approach becomes technologically impracticable.

In the very early days of supersonic wind-tunnel testing (at Mach numbers up to 2.0), it was found that the natural moisture content in the air would condense in the nozzles, but not until a significant level of supersaturation had been reached. It was then expected that flowing air also would supersaturate prior to condensing. Instead, however, in the early low hypersonic Mach number studies (up to Mach numbers of about 7.0), air was found to condense generally very soon after the saturation conditions were reached. However, at elevated hypersonic Mach numbers (greater than 8), it was eventually shown that air supersaturation does occur (Ref. 1) and, in fact, may reach very high levels. The importance of this fact is that, by testing with air in the supersaturated state, the required preheat temperatures are considerably lowered.

A further ARL study of air condensation has recently been completed. The objectives of this study were: (1) to extend the results of the existing experimental study to conditions of greater Mach number(s) and lower pressure(s); and (2) to explain the observed characteristics of the condensation phenomenon. Using one of the small (5-inch-nozzle-diameter) ARL hypersonic wind tunnels, the stream pressure p_c and temperature T_c conditions at the point of condensation onset were determined over a Mach number range of about 14.0 to 18.5. These results are presented in Fig. 1 where p_c is plotted against T_c. (The new ARL data are represented by the clear circular symbols appearing near the bottom of the Figure.) A significant point is that there is a strong change in the experimentally determined onset curve at a pressure of about 0.07 mm Hg. Also, it is seen that the supercooling, which is indicated by the horizontal spread between the onset curve and the air saturation curve (also shown in Fig. 1), remains essentially constant at pressures lower than about 0.05 mm Hg. However, the supersaturation (defined as the ratio of the pressure at the onset to the corresponding saturation pressure at the onset temperature), continually increases with decreasing pressure since the slope of the saturation curve increases with decreasing pressure.

A theoretical analysis, based on the theory of spontaneous nucleation in a supersaturated vapor, indicated a strong influence of expansion rate on the onset of condensation of a pure vapor; this was substantiated by experimental observations. It was shown that the observed supersaturation was larger in the faster expansions.

The theoretical study also led to the establishment of a correlation parameter for the test results. This parameter, which related the time rate of expansion to the pressure at the onset of condensation, strictly correlated

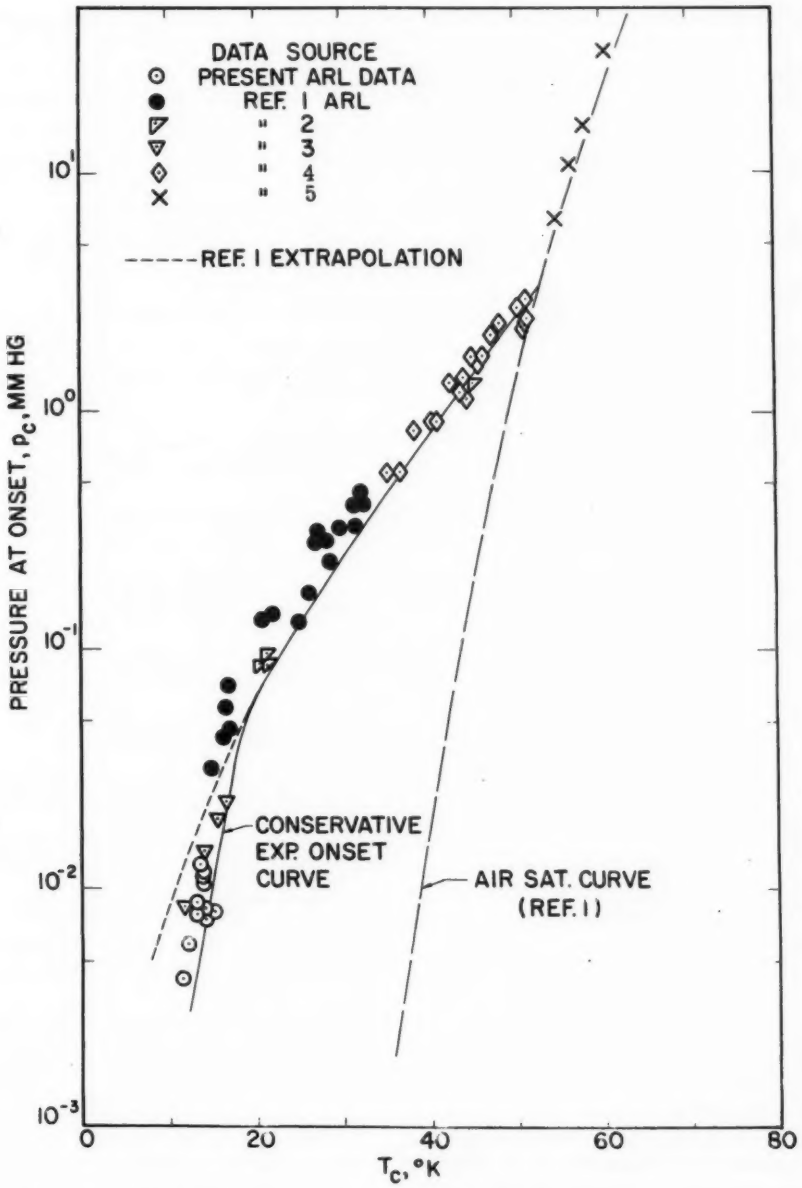

Fig. 1. Stream Pressure and Temperature at the Onset of Condensation

the air condensation results except for those cases where little or no supersaturation existed; the lack of correlation for these cases suggested that here condensation was not due to the same physical mechanism (spontaneous nucleation) which occurred at the higher supersaturation values. This, in turn, led to the interpretation that, for these noncorrelating cases, condensation occurred on foreign nuclei. Further, it appeared that the CO_2 and H_2O existing in the dried wind-tunnel air served as the seeding agents for promoting condensation of the primary components of air, nitrogen and oxygen.

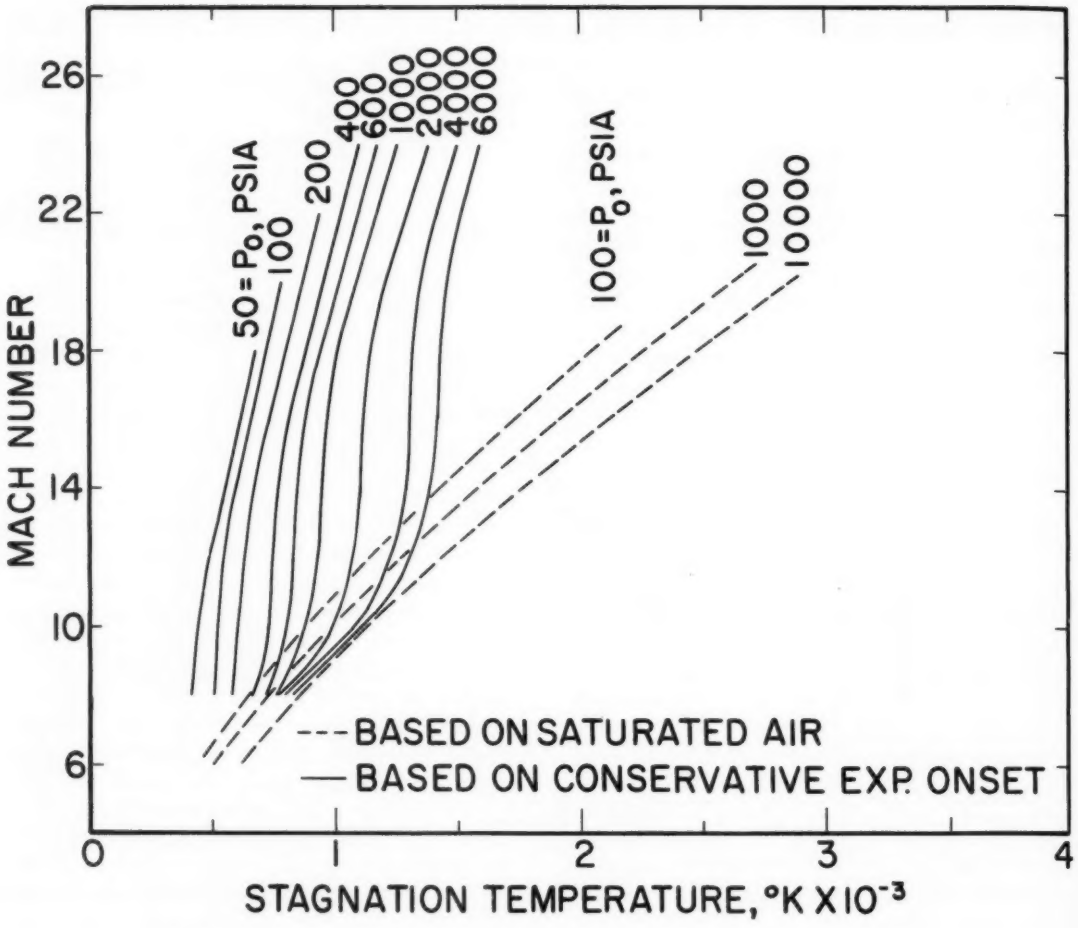

Fig. 2. Stagnation Temperature Corresponding to Onset of Condensation

Referring again to Fig. 1, the behavior of the onset curve may be briefly explained as follows:

At pressures greater than about 3.5 mm Hg, condensation occurs through the seeding process just mentioned. However, if the stagnation conditions are such that the saturation pressure in the stream becomes lower than 3.5 mm Hg, the seeding process begins to be inefficient and some supersaturation will be attained before condensation occurs. At still lower pressures, the seeding effect of the CO_2 and H_2O decreases further and is usually lost completely at pressures below 0.06 mm Hg; here, condensation occurs through spontaneous nucleation, even if the test medium is dried natural air.

Based on the "conservative experimental onset curve" shown in Fig. 1, a revised generalized chart has been prepared (Fig. 2) which indicates the stagnation temperature at which air (or nitrogen) condensation should appear at the nozzle exit as a function of Mach number; stagnation pressure P_0 is shown as a parameter. The solid lines represent the operational stagnation temperature required if supersaturated air is used; the dashed lines show the temperature required if supersaturated conditions are to be avoided.

It is immediately evident that greatly reduced stagnation temperatures may be employed for hypersonic wind-tunnel operation.

A paper describing the present study was presented at the Ground Installations Session of the XVIth International Astronautical Congress held in Athens, Greece, September 1965. Also, a more detailed description of these studies will be available in ARL Report No. 65-159. ★

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Electrofluid Dynamic (EFD) Power Generation Processes

MAURICE O. LAWSON

Thermomechanics Research Laboratory, ARL

The stringent performance requirements of space power systems have focused attention on direct energy-conversion processes which do not employ moving mechanical parts. Two promising fluid dynamic fields of direct energy conversion are those of magneto- and electrofluid dynamics. In magnetofluid dynamic processes, the fluid dynamic energy is transformed directly into electrical energy by passing an electrically conductive working medium through a magnetic field (Fig. 1). In electrofluid dynamic (EFD) processes, fluid dynamic energy is directly transformed into electrical energy by passing a working medium containing unipolar ions or charged colloids through an electrostatic field (Fig. 2).

Magnetofluid dynamic processes show promise of high power density and favorable conversion efficiencies if the working substance has high conductivity combined with low mass density. This implies very high

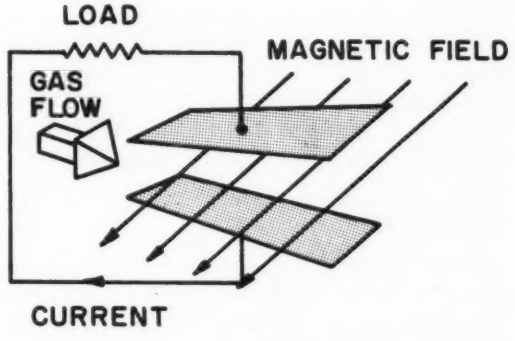

Fig. 1. M.H.D. Generator

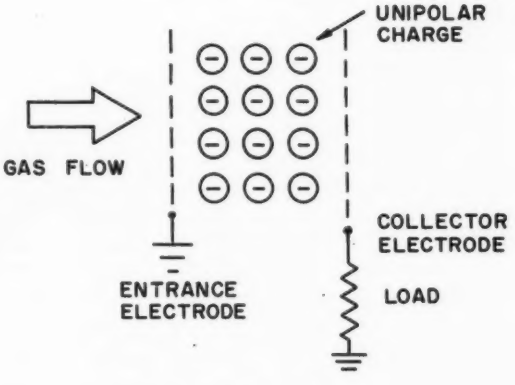

Fig. 2. E.F.D. Generator

temperatures and high ionization levels, which may require seeding with a low work-function material such as cesium. The performance of magnetofluid dynamic processes is characterized by high current density and relatively low voltage.

The characteristics of electrofluid dynamic processes are quite different in that EFD processes typically produce high voltage and low current density; also, EFD processes do not require high gas temperatures, thereby enabling nuclear heat sources to be readily used in closed cycles.

The basic EFD process is similar to that

of a Van de Graaff generator in that the EFD process in the conversion section corresponds to the functions of the mechanically driven belt in the Van de Graaff generator. However, the gas speed in an EFD process can be far higher than the belt speed of a Van de Graaff generator. In addition, the electrically charged particles in an EFD process are distributed throughout the volume flow of the working medium rather than being concentrated on a belt surface. These conditions result in power densities in EFD processes that are many orders of magnitude higher than those obtainable with Van de Graaff generators.

Some of the major aspects resulting from the analytical investigations are as follows (see references): since processes which employ only charges of one polarity are limited in electric-charge density by space charge effects, the performance characteristics are low current density, high electrostatic field strength, and high voltage (on the order of 10^5 to 10^6 volts). To transport one elementary electric charge against such a high electrical potential, the combined fluid dynamic energy of a great number of neutral molecules of the working substance is required. For example, in a closed-cycle EFD energy-conversion process, the useful energy per molecule of the working substance may be on the order of one one-hundredth of an electron volt, and the electric potential may be 10^6 volts. Under such conditions, the combined useful energy of at least 10^8 neutral molecules of the working substance is needed to transport one elementary electric charge from the grounded entrance electrode to the collector electrode. From these considerations, it follows that the ionization levels in EFD processes which employ unipolar ions are very small, on the order of about 10^{-8}.

Combining the useful energy of about 10^8 neutral molecules to transport one elementary charge against the high field strength in the conversion section requires an effective coupling. Two coupling methods are being studied.

One utilizes viscous coupling between the working substance and the electric-charge carriers. Here, the charge carriers may be ions or, for obtaining a more effective viscous coupling, electrically charged colloids. The charged colloids are produced, for example, by vapor condensation around ions, the amount of condensed vapor being a small fraction of the total mass of the working substance.

The second method of coupling corresponds to what may be termed rigid coupling between the electrical charges and the working medium. In this process, the available thermal energy is brought into the form of kinetic energy of charged particles of suitable charge-to-mass ratio. The charged particles can be produced in many ways, for example, by condensation of a major mass fraction of the working substance around ions. Processes of this type are referred to as ballistic EFD processes, since the charged particles proceed through the conversion section along a ballistic path.

ARL is conducting a combined analytical and experimental research program on the production of charges or charged particles, determination of gas mixtures of suitable properties, determination of scaling and similarity laws, and efficient over-all cycles of conversion from heat energy to electrical energy. This research was initially supported under the ARL In-House Independent Laboratory Research Funds. ★

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PROFILES

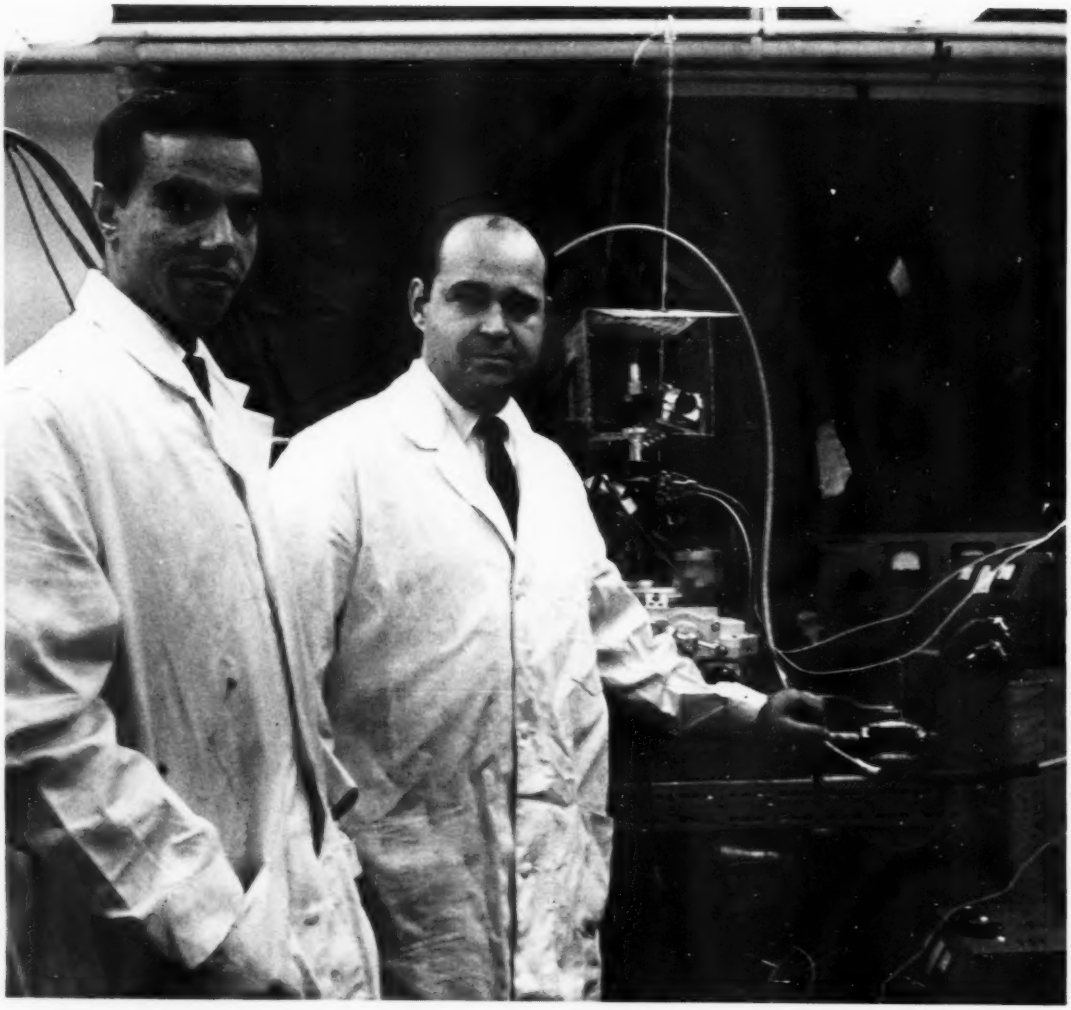
1st Lt Thomas F. Jerrick, a research physicist with the Optical Physics Laboratory, AFCRL, is currently studying mode structure and spiking behavior in solid-state lasers. His work involves trying to find a mathematical description for the effects of an active medium in an optical resonator on both the mode shapes and spiking. Lt Jerrick has a B.S. degree in Physics from St. Louis University (1962), and an M.S. degree in Space Physics from AFIT (1964). His article, "Lasers and the Hall Effect," appeared in the December 1965 issue of the Review.

PROFILES

Mr. John H. Conover, a research meteorologist with the Meteorology Laboratory, AFCRL, is presently working in the field of satellite meteorology. His current studies are concerned with the reflective properties of clouds in the visible portion of the spectrum as part of the over-all interpretation of cloud photography obtained from satellites. Mr. Conover attended Swarthmore College from 1934 to 1936. Before coming to AFCRL in 1959, he worked at Harvard's Blue Hill Meteorological Observatory. His latest work there was on the relationship of high clouds to the jet stream. He is listed in American Men of Science, and is a professional member of the American Meteorological Society. He has written numerous publications. In his early career, these dealt with meteorological instrumentation. Since then, they have been almost entirely on clouds and their interpretation. Some of Mr. Conover's recent work was described in the article, "Curious Cloud Structure," which appeared in the December 1965 issue of the Review.

Dr. George Gyarmathy, an ARL scientist with the Thermomechanics Research Laboratory, is currently working on experimental studies regarding the complicated flow pattern existing in the vortex chambers developed by ARL (design: Dr. H. von Ohain), including the size and behavior of condensed particles formed in the vortex. The aim is to improve the separation efficiency of the chambers. Theoretical studies with F. L. Daum, also at ARL, showed that the behavior of air at low pressure is due to spontaneous condensation. At present, they are trying to show that the high-pressure behavior can be explained by condensation on CO_2 and H_2O particles which form further upstream in the wind tunnel. Dr. Gyarmathy received his Ph.D. from the Swiss Federal Institute of Technology, Zurich, 1962, and a Diploma in Mechanical Engineering from the Technical University of Budapest, 1956. He has given several presentations in his field of expertise, and has also published a number of papers. In this issue of the Review, he is coauthor of the article, "Air Condensation in Rapidly Expanding Hypersonic Flow."

Mr. Maurice O. Lawson, Thermomechanics Research Laboratory, ARL, currently performs and is responsible for research on flow through supersonic rotating cascades as well as fluid dynamic research on origination of high-temperature gas. He performs research in the area of direct conversion of fluid dynamic energy to electrical energy. Mr. Lawson was graduated from Indiana University with an A.B. in Mathematics. He also has 27 hours with the Ohio State Graduate Center where he did graduate work in fluid dynamics, thermodynamics, and mathematics. Mr. Lawson has had extensive research experience in internal fluid dynamics. In 1948 he began a close working association with Drs. Wattendorf and von Ohain at ARL. He has made major contributions to the theory of design of high-performance transonic inlet compressor stages and supersonic stages and energy-conversion phenomena involving fluid mechanics energy. He has several publications to his credit. In this issue of the Review, Mr. Lawson discusses "Electrofluid Dynamic (EFD) Power Generation Processes."



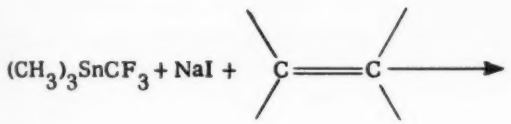
From left to right are shown Dr. Farid Hushfar and Dr. A. T. Stair, both of the Optical Physics Laboratory, AFCRL. Dr. Hushfar holds a B.A. degree in Physics from the University of Wisconsin (1955), and a Ph.D. degree from the University of Pittsburgh (1961). After one year of postdoctoral work at New York University and two years of industrial experience, he joined AFCRL in 1964. He is presently involved in research aimed at the production of low-energy intense molecular beams and their application to atomic and molecular collisions. Dr. Stair holds a B.A. degree in Mathematics (1952) (Phi Beta Kappa), and a Ph.D. degree with a major in Physics (1956), both from the University of Oklahoma. He served two years as a first lieutenant in the Air Force at AFCRL, and has been a research physicist there since 1958. He has been involved in the measurement and analysis of the optical/infrared emissions of high-altitude nuclear detonations. In 1961, he started a basic laboratory research program to study nonequilibrium radiative phenomena, particularly at infrared wave lengths. Out of this program developed an awareness of the need to develop molecular beams which represent one of the most fundamental probes for low-energy physics and/or high-energy chemistry. The article, "Molecular Marksmanship," which appeared in the December 1965 issue of the Review, described some of the work by Dr. Hushfar and Dr. Stair in molecular-beam research.

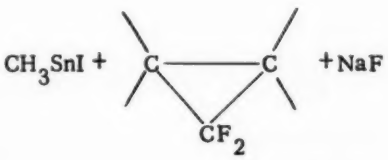
DIHALOCARBENES

DR. ANTHONY J. MATUSZKO
Directorate of Chemical Sciences, AFOSR

Research on organometallic chemistry at the Massachusetts Institute of Technology (MIT) has resulted in the generation of difluorocarbene, CF_2, under the mildest conditions reported thus far. The generated CF_2 reacts in the presence of olefins to form gem-difluorocyclopropanes in very good yield. (The gem-difluoro- refers to the attachment of both fluorines to the same carbon atom.) This work was done by Dr. Dietmar Seyferth and his co-workers as part of a continuing study of the "extrusion reaction" under a grant from the Directorate of Chemical Sciences, AFOSR.

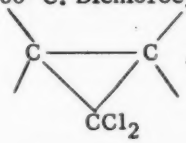
The "extrusion reaction" involves a general decomposition of organometallic compounds containing halogenated organic substituents in which the organic portion separating a metal atom and a halogen is extruded either thermally or photochemically. For example, in the formation of CF_2, trimethyl(trifluoromethyl)tin (I) was decomposed at 80° C; the CF_2 reacted with the olefin in the reaction mixture to form a gem-difluorocyclopropane: (1)





Sodium iodide serves to release CF_2 in the reaction. The product yields were over seventy per cent with the olefins tried.

Similar reactions were tried on organomercurials, such as $C_6H_5HgCCl_3$, with olefins in the presence of sodium iodide; the reaction temperatures were 30° C rather than 80° C. Dichlorocyclopropane derivatives,



, were formed in yields which were over ninety per cent.

The reactions carried out by the MIT group were conducted in a nonbasic medium. This is particularly significant since basic conditions (or higher temperatures) are generally used in the generation of halocarbenes. However, many organic and inorganic reactants and reaction products are not stable to basic conditions. Hence, the organometallic decomposition leading to these reactive species has important advantages and should prove valuable in the synthesis of new materials, especially in the preparation of gem-difluoro derivatives. The mild conditions for reaction could find useful Air Force application in the dihalomethylation of residual olefinic bonds in high-temperature polymers to increase their thermal stability. ★

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HIGH AND LOW (high-temperature research in chemistry)

DR. WILLIAM L. RUIGH
Directorate of Chemical Sciences, AFOSR

The United States Air Force, in accomplishing its mission, is forced to deal with matter under extreme conditions, particularly of temperature. At one end of the temperature scale the Air Force has had to solve the problems of operating with liquid hydrogen as a rocket propellant. In the laboratory, liquid helium at 4° K is used to cool and thereby reduce the random noise in using semiconductors as ultrasensitive detectors of light and radiation. The special scientific, technical and engineering conditions dealt with at low temperatures are called cryogenics.

At the other end of the scale is the area of

high-temperature chemistry. The Air Force has many problems, particularly those involving the strength of materials at high temperatures. Examples are the wing structures of supersonic planes, the materials of construction in a nuclear-propulsion reactor and last, but not least, the ablative and heat-resistant materials used in nose cones of missiles and the surface of re-entry space vehicles.

From its inception, the Directorate of Chemical Sciences, AFOSR, has recognized the needs of the Air Force for high-temperature materials and has sponsored long-range research in this area. One of the first contracts to be negotiated by the Directorate of Chemical Sciences (then under the Air Research and Development Command) was with Professor George J. Janz of the Department of Chemistry, Rensselaer Polytechnic Institute, Troy, New York. The purpose of this contract was essentially to set up a laboratory to study molten salts at high temperatures in order to understand their structure and behavior.

One of the first accomplishments of Dr. Janz was to design and construct an apparatus for the precise simultaneous measurement of the surface tension, viscosity, and density of fused salts up to 1000° C. A schematic diagram of the apparatus can be seen in Fig. 1.

The essential features are the density bob A, of special design to permit precise contact with the melt; a crucible of continuously varying height, B; and C, a visible-scale, recording, analytical balance. This arrangement has been used with molten alkali metal salts at temperatures up to 1000° C. The detail of the surface-tension bob is shown in (b). The bob is machined from a massive block of metal to avoid cracks which might introduce errors in measurements.

Later, Dr. Janz built an apparatus and developed techniques for measuring infrared and Raman spectra and the electrical behavior of molten salts. In addition to the laboratory data on fused salts, Dr. Janz made a monumental contribution to the science of high temperatures by publishing two comprehensive reports: (1) "Molten Salt Data--Electrical Conductance, Density, and Viscosity," and (2) "Bibliography on Molten Salts." The latter is an invaluable tool for scientists and engineers working in high-temperature areas.

The "Molten Salt Data" report is a critical compendium of the "best" values for molten

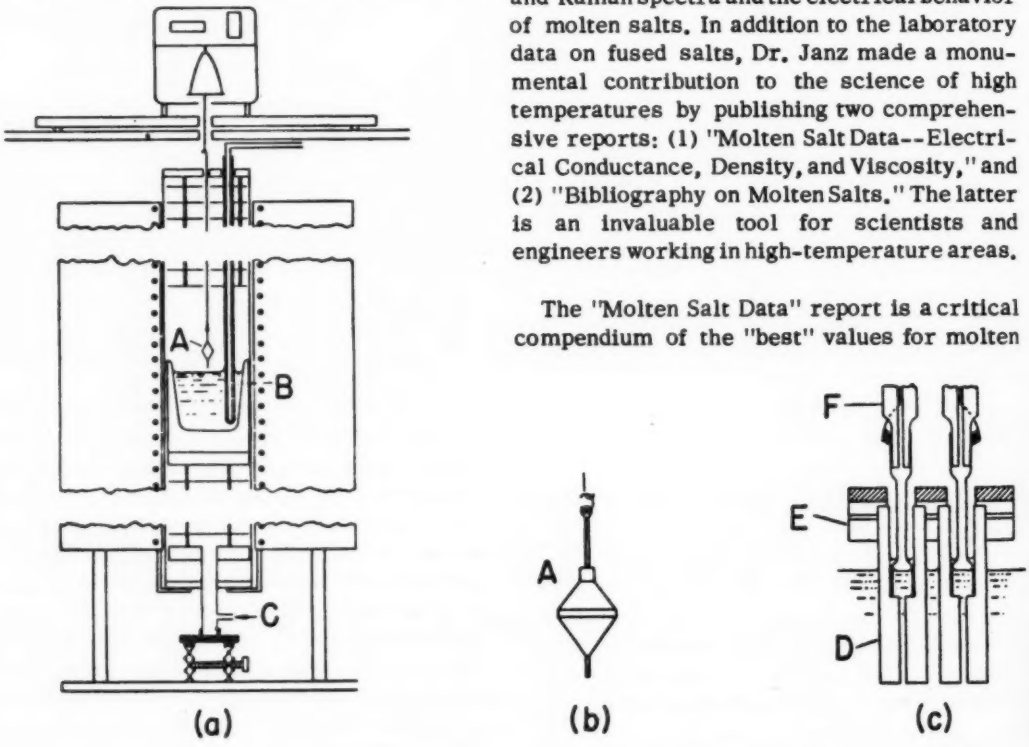

Fig. 1. Experimental Assemblies for Precise Measurement of Surface Tension, Density, and Electrical Conductance of Molten Salts.

salts. Dr. Janz has reported data from the literature supplemented by experimental results in his own high-temperature laboratory. The results were checked for accuracy by a computer program--an abstract follows:

"Conductance, density, and viscosity data at round values of temperature (^{o}K) are given for some 126 inorganic compounds as Single-Salt Melts (Fluorides, 15; Chlorides, 34; Bromides, 20; Iodides, 23; Oxides, 7; Sulphates, 5; Nitrates, 7; Carbonates, 3; and Miscellaneous, 12). Equations expressing the temperature dependence of these properties for the single-salt melts are also given. For mixtures of these salts, the binary systems that have received attention are listed; numerical values for these mixtures are not given, but are referenced."

All workers in the field of high temperatures owe a debt of gratitude to Dr. Janz for these comprehensive reports. ★

balloon-borne communications relay

CHARLES S. TILTON, Aerospace Instrumentation Laboratory, AFCRL

AFCRL has successfully demonstrated the use of balloons as high-altitude relay stations for over-the-horizon UHF communications. The demonstration of balloons as relay stations for special tactical communications' use took place 16 November 1965 at AFCRL's Holloman AFB, N.M. balloon-launch facility.

The balloon reached an 80,000-foot altitude where, for several hours, it relayed voice and teletype messages between Ft. Huachuca, Arizona, and Reese AFB near Lubbock, Texas, a distance of about 500 miles. The test was made to evaluate a new communications system being developed by AFCRL and the Air Force Systems Command. The objective of the test program is to demonstrate techniques available for solving some of the command and control problems associated with limited warfare.

The balloon-relay system works basically the same way as an active communications satellite. When radio relay equipment is placed at a high altitude, the line-of-sight distance between ground stations and this equipment is greatly increased, enabling it to serve as a communications link for VHF and UHF signals transmitted between widely separated points.

Distances greater than 500 miles can be obtained by using several balloons, and by floating them at higher altitudes. The maximum distance over which ground stations can communicate via a single balloon is about 780 miles--a distance determined by the 100,000-foot altitude reached by conventional balloons of moderate size and cost.

Under proper weather conditions, balloons can remain virtually stationary for hours, and even days, facilitating continuous, reliable communications between ground stations; balloons tethered to the ground are also being considered.

The basic instrument used in the test program is a compact, lightweight UHF repeater that operates at frequencies between 225-400 Mcps, receiving signals from one ground station and retransmitting them to another. Balloon-launch facilities, support, and vehicles to carry the UHF repeater aloft are provided by AFCRL under a program directed by the author and James C. Payne of AFCRL. Ground communications equipment and technical support are provided by AFSC's Rome Air Development Center.

Further tests of the system using both tethered and free-floating balloons will be made during the coming year. ★

These pictures are only indirectly related to the story on "Balloon-Borne Communications Relay." There are many applications for tethered balloons. It is entirely feasible to attach a simple relay system to a tethered balloon permitting it to ascend several hundred feet and thereby gaining perhaps 50 miles greater distance in a relay communications scheme. The two tethered balloon configurations shown, however, were not used in the balloon relay tests discussed in the story.

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